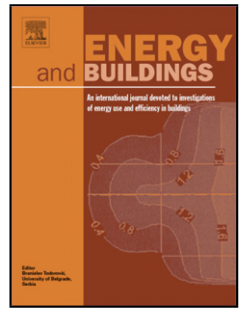

Title: Quantifying electrical energy savings in offices through installing daylight responsive control systems in hot climates

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Quantifying electrical energy savings in offices through installing daylight responsive control systems in hot climates

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Abstract

Lighting is considered as one of the most important issues in reducing energy consumption of a building. It is estimated that electrical lighting consumes 25-40 percent of the total electrical energy in a typical commercial building in the United States. Over the last three decades, there has been a growing concern about reducing energy consumption associated with artificial lightings. Daylighting could be considered as a cost-effective alternative to artificial lighting which not only reduces the demands for electrical energy, but also provides occupants with a pleasant, attractive, and a healthy indoor environment. Through installing sensors and controllers, daylighting is able to reduce and even eliminates the use of artificial lighting needed to deliver sufficient illuminance levels in an office. Present study is a simulation based research that investigates the impacts of various types of daylighting controllers on enhancing total and lighting electrical energy consumption of office buildings located in hot climates. Effects of Dimming (5%, 10%, and 20% light), On/Off, and Stepped control systems are evaluated in this study. E-Quest is used as the energy simulation tool to calculate and compare electrical and lighting energy consumption. In order to assess the effects of daylight control systems in humid and arid hot climates, Miami, Phoenix, and Houston, located in ASHRAE 90.1 climate zones of 1, 2b, and 2a respectively, have been chosen as three locations for the prototype building. The prototype building is a four-story open office building measuring 18m wide x 36 m long x 15 m high oriented along east-west axis. The window to wall ratio of 20, 40, 60 and 90 percent in all directions are assessed. Windows consist of horizontal shading in all façades as well as blinds in those of East and West. Results of this study demonstrate that in all studied cities installing daylighting controllers in office buildings significantly reduces electrical energy consumption of the building particularly that of lighting.

Keywords: Daylight responsive control systems; Lighting, Electrical energy savings; Cooling energy; Hot climates

1. Introduction

In the past decades, there has been a growing concern regarding energy consumption of buildings and its environmental impacts such as carbon emission, Urban Heat Island effects, and global warming. Around 19 percent of total national energy use and 46 percent of building primary energy in the United States consume in commercial sector [1]. Based on 2012 Commercial Buildings Energy Consumption Survey (CBECS 2012) released in 2016 [2], it is estimated that artificial lighting accounts for 10 percent of total energy and 17 percent of electrical energy consumption in commercial buildings. In addition, lighting has also secondary impacts on cooling and heating energy consumption due to the heat produced by electric lights. However, it is difficult to quantify these impacts as it significantly depends on the building characteristics, operating conditions, and climates. Generally, reducing lighting energy results in increasing heating and decreasing cooling energy demands of a building [3]. Therefore, lighting is as an important factor in reducing total energy consumption of a building particularly in hot climates where space cooling load is enormous [4-5].

Several studies demonstrated that daylighting could be a cost-effective alternative to reduce electrical energy consumption associated with lighting. With installing sensors and controllers, natural light helps to decrease or even eliminate the electrical energy required to provide sufficient illuminance level in an office environment [6-8]. There is a variety of assertions in the literature regarding the amount of energy that could be saved from daylighting depending on the control strategy. Based on a study conducted by Jennings et al. [9] on a 21-story office building in San Francisco, a daylight Dimming control system could save up to 26% of electrical lighting compared with manual switching. In a simulation based study, Szerman [10] found that using daylight controllers in office buildings could reduce lighting and total energy consumptions of the building by 77% and 14% respectively in moderate climates. Roisin et al. [11] investigated the potential energy savings in offices through applying various photosensors and occupancy sensors in three cities in Europe (Brussels, Stockholm, and Athens). Their findings concluded that 45-60 percent of electric energy could be saved depending on the orientation and location of the building. South oriented windows could save more electrical energy compared to those with north facing windows. In another research, Ferreira et al. [12] compared the energy savings from using two daylight controllers including Dimming and Switching in a commercial building located in Ibope, Brazil (tropical climate). They concluded that both systems are effective in reducing total electric energy consumption, but more energy (23%) could be saved with a dimmer controller compared to a switching controller (16%).

In addition, daylight sources are more efficacious than any electric light sources in that daylight carries with it less heat than electric light sources for the same illuminance level. Consequently, the impact on cooling demand will decrease with a daylighting strategy [13]. This is specifically beneficial for buildings located in hot climates where cooling demand is typically enormous [14-16]. Moreover, having the color rendering index of 100 percent, daylighting is the best source of light [17]. It has been proven that daylighting enhances occupants' health and well-being and improves office workers' productivity [18]. Considering all these benefits, there has been a growing interest among architects and engineers in incorporating natural light in buildings to enhance buildings' energy consumption and provide occupants with a healthy and productive environment.

Literature indicates that the amount of energy saving due to an active utilization of natural light in an office space is strongly related to the type of control system used for that building. Only few of these studies, however, have compared the impacts of different types of daylight control systems. Our study is a simulation based investigation of the potential energy saving associates with the use of three control strategies, namely Dimming, Automatic On/Off, and Stepped in hot climates.

2. Research Methods

The purpose of the present study is to evaluate the impacts of various types of daylight control systems on lighting and total electrical energy consumption of an office building in hot and arid climates. In this regard, three cities of Miami, Houston, and Phoenix in the United States have been considered as three locations for the virtual office. Although all three cities are located in hot climates, their ASHRAE Climate zones are different. Table 1 shows each city's climate zone and conditions.

Table 1
Cities' climate zones

City	ASHRAE Climate Zone	Description
Miami	1A	Very Hot – Humid with SI Units 5000 < CDD10ºC
Houston	2A	Hot – Humid with SI Units 3500 < CDD10ºC ≤ 5000
Phoenix	2B	Hot – Dry with SI Units 3500 < CDD10ºC ≤ 5000

Moreover, Table 2 provides more information about the climate characteristics of these three cities. This data has been taken from the cities' weather data files (.ewp). We uploaded these files in Climate Consultant 6.0 program to obtain presented data in Table 2. As shown, selected cities have high annual average global horizontal solar radiation, global horizon illumination and direct normal illumination. Table 2 also illustrates selected cities' sky cover range. Sky cover is defined as the percentage amount of the sky covered by opaque clouds valid for the indicated hours [19]. Sky cover rang has a negative correlation with annual solar radiation and illumination [20]. Therefore, Phoenix with the lowest sky cover range (24 percent) among three selected cities has the highest annual solar radiation and illumination due to more clear sky condition throughout a year. In contrast, Houston receives the least amount of solar radiation and illuminations compared to Phoenix and Miami, as a result of higher sky cover range (52 percent) and annual cloudy sky hours. Since, solar radiation and illumination as well as sky cover range are measures of daylight availability in cities, it appears there is a good opportunity to utilize daylighting in office buildings in these three cities.

Table 2
Cities' solar radiation and illumination

City	Annual Average Global Horizontal Solar Radiation (Wh/m^2)	Annual Average Global Horizon Illumination (lux)	Annual Average Direct Normal Illumination (lux)	Sky Cover Range
Miami	4726	41853	34452	48%
Houston	4246	37509	29957	52%
Phoenix	5589	47900	55716	24%

2.1. Office Building

According to CBECS 2012, offices are the most prevalent building type (18.2%) in commercial building sector. In addition, around 99.3% of offices in the United States are 1 to 9-story buildings [2]. Hence, for this study, a virtual 4-story office building is considered for simulation. The office is a rectangular-shape building measuring 18 m wide x 36 m long x 15 m high oriented along east-west axis (Figure 1). Tables 3, 4, and 5 show construction details, building operation schedules as well as HVAC system design respectively.

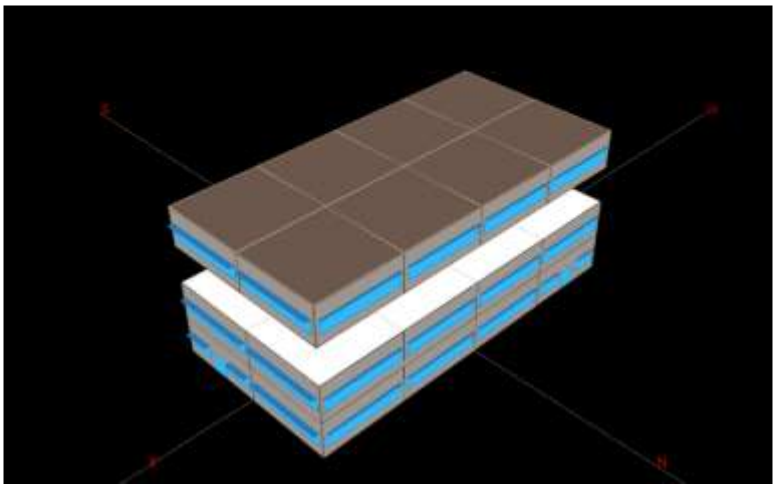

Figure1. Virtual 4-story office building modeled in E-Quest with WWR of 40%

Among various details shown in Table 3, insulation is a significant factor affecting the energy consumption of the building. Insulation is specified by R-Value which measures the resistance to the flow of heat. For this simulation, we considered the R-Value of R-3.35, R-3.35, and R-2.29 (K.m^2/W) for the roof, floor, and walls respectively.

Table 3
Summary of details for the virtual office building

Parameters	Description / Value	
Building Type		Mid-Rise Office
Activity		Open Office (Design Max Occup: 10 m^2/person; Design Ventilation: 15:00 cfm/per)
Construction	Roof	Metal Frame, >60 cm o.c
	Floor	15 cm Concrete
	Exterior Walls	Metal Frame, 2x6, 60 cm o.c.
Insulations / R-Value	Roof	R-3.35 (K.m^2/W)
	Floor	R-3.35 (K.m^2/W)
	Exterior Walls	R-2.29 (K.m^2/W)
Interior Finish		Carpet
Surface Reflectance	Ceiling	0.8
	Floor	0.2
	Interior Walls	0.5

Table 4
Building operation schedule

	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Holidays
Building Operation Schedule	8:00-17:00	8:00-17:00	8:00-17:00	8:00-17:00	8:00-17:00	Closed	Closed	Closed

Table 5
HVAC system design

HVAC System	Description / Value	
Cooling Source		Chilled Water Coils
Heating Source		Hot Water Coils
System Type		Standard VAV with HW Reheat
System's Thermostats (^oC)	Occupied	Cool: 25 – Heat: 21
	Unoccupied	Cool: 30 – Heat: 18
Cooling Design Temperature (^oC)	Indoor	24
	Supply	13
Heating Design Temperature (^oC)	Indoor	22
	Supply	35
Minimum Design Flow ($m^3/(s.m^2)$)		0.00254
VAV minimum Flow		40%
Schedule	Weekdays	7:00-18:00
	Weekends/Holidays	Off

The office includes windows in all directions. Previous studies demonstrated that the effectiveness of daylight controllers depends on several factors including windows shape and area [21]. The window to wall ratio (WWR) of

20, 40, 60, and 90 percent were evaluated in this study. To optimize the results of simulations, all windows consist of a 0.6m horizontal shading in all façades as well as light color vertical blinds in those of East and West to reduce sunlight glare. The schedule of the vertical blinds in different seasons has been indicated in Table 6. The glazing type of windows located in South, West, and East facades is double bronze 6mm with 6mm air (Visible Light Transmittance: 47%; U-Value: 2.7 $W/m^2.K$) while for North windows glazing type of double clear 6mm with 6mm air (Visible Light Transmittance: 79%; U-Value: 2.7 $W/m^2.K$) was selected.

Table 6
Vertical blinds' schedule

Seasons		% Blinds Closed			
		North	South	East	West
Winter (12/21 – 3/20)	When Occupied	0	0	40	40
	When Unoccupied	0	0	80	80
Spring/Summer (3/21 – 9/20)	When Occupied	0	0	60	60
	When Unoccupied	0	0	80	80
Fall Remaining	When Occupied	0	0	20	20
	When Unoccupied	0	0	80	80

2.2. Daylight Control Systems

As Leslie stated [22], daylighting does not save energy. Energy consumption could be reduced by switching off or dimming down the electrical lights. In this regard, daylight control systems have been demonstrated as an effective method to design energy efficient buildings [23]. The main purpose of daylight controllers is to maintain required lighting levels [24] through adjusting artificial lights output based on the alteration in the available daylight. Generally, there are two types of daylight control systems: Dimming and Stepped (Switching). Dimming control systems allows the level to be set between a minimum and maximum range through dimming while Stepped systems provide for either on or off status. Both systems contain three basic components including a photosensor, lighting controllers and dimming ballast or relay unit. As photosensor finds luminous flux, translates this into a signal that is sent to the controller. Then, the controller procedures the signal and switches a predetermined proportion of lights off/on or defines the desired dimming level [25] (Figure 2).

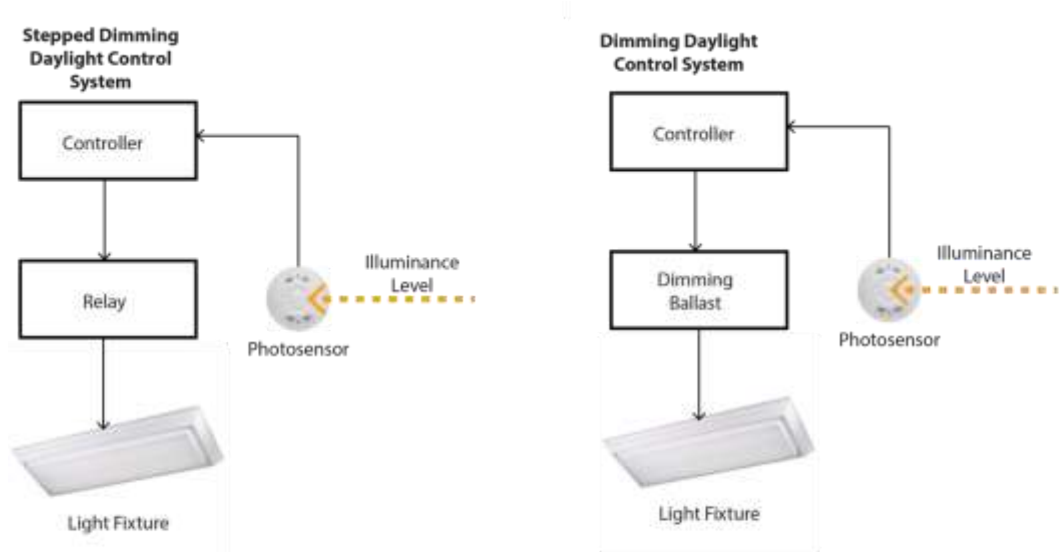

Figure 2. Diagrammatic illustration of Stepped and Dimming daylight control systems

A Stepped system is designed to switch artificial lightings on as the illuminace level is lower than a determined level and off when it is equal or higher [13]. There are various types of Stepped daylight control systems based on the portion of fixtures that switches on and off as well as the numbers of scheduled on and off steps.

As an instance, depends on available daylight in a specific daylight zone, 33%, 50%, or 66% of the lights might be switched off. The algorithm is various based on the space activity and required illuminance levels as well as lighting fixture lumen outputs [21]. The main problem with this type of control system is that under unstable weather conditions at which the lighting level associated with daylighting changes frequently, the rapid and frequent switching of lights on and off may cause occupants' disruption and decrease lamp life.

Dimming controllers adjust the lumen output of the lamps based on the prevailing illuminance level. Although lumen output could be approximately assumed proportional to power consumption, the lamp could not be dimmed 100 percent and to total extinction [13, 26]. Therefore, the system efficiency reduces as electrical lights are dimmed. For instance, at 5% brightness, the light might still consume 21% of the power (see Table 6). Figure 3 shows the correlation between the light output and the power input for an ideal operation of a Dimming control system. As illustrated, under the ideal condition, there is linear correlation between light output and corresponding power input [27, 28]. For other conditions, the lighting power consumption could be quantified with the input values of power input fraction, light output ratio, target illuminance, working plane illuminance and full light output based on the linear correlation [28, 29]. In addition, Dimming control systems are significantly more expensive than Stepped ones. The reason is that these systems need a dimmable ballast which are not used in most of the conventional buildings [13].

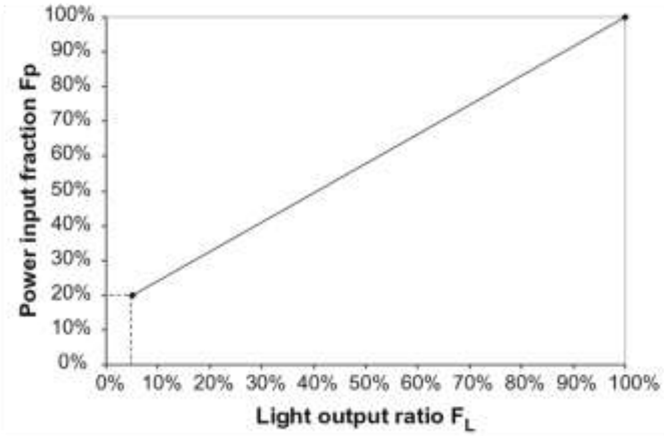

Figure 3. Correlation between light output ratio and power input fractions for an ideal operation of a Dimming control system [13].

Moreover, daylight control systems could be categorized based on the algorithm of control. Generally, there are two types of control algorithms: (1) closed loop and (2) open loop. The closed loop daylight control algorithm receives illuminance levels of the defined daylight zone including both electrical lighting and daylighting and adjusts the Dimming level or switches the lamps in order to achieve and maintain the required illumination. In contrast, in the open daylight control algorithm, the controllers are placed and oriented to only detect available daylight levels and not receive any feedback from electrical lights installed in the daylight zone. Therefore, the system is not able to measure the total available lighting levels. Based on the available daylight, the control system approximates total illumination and sends the corresponding signal to the controller to provide corresponding illumination [21]. Figure 4 illustrates diagrams of closed and open loops respectively.

For this study, we compared energy saving potential of 6 Stepped and 4 Diming daylight controllers available in E-Quest in order to find the most energy efficient control systems for offices located in hot climates. Selected daylight control systems are indicated in Table 7. As Table 7 shows a wide variety of daylight control systems has been selected to have a sufficient comparison group and determine the most beneficial daylight controllers in terms of lighting, cooling, and total electrical energy savings. Moreover, all simulations have run in a closed loop algorithm as daylighting function of E-Quest works only based on a closed loop system.

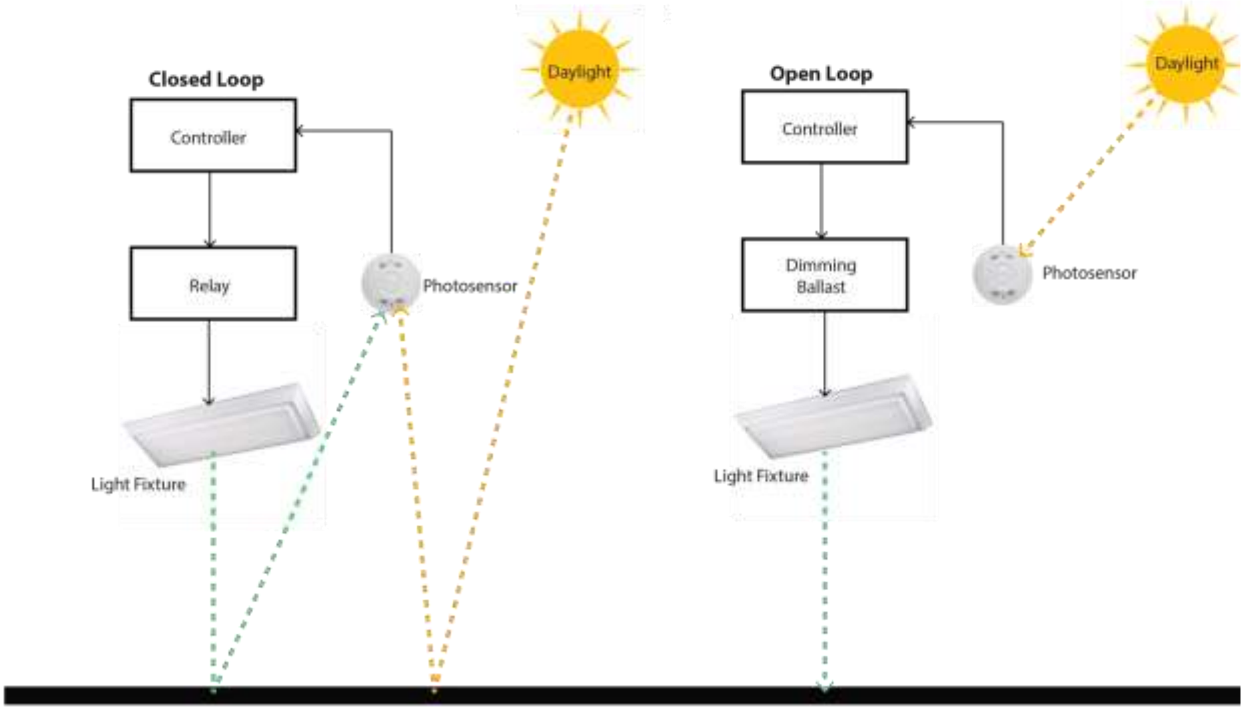

Figure 4. Diagrammatic illustration of closed and open loop algorithms for daylight control systems.

Table 7
Evaluated Daylight Control Systems

Stepped	Dimming
Type	Type
On/Off	Down to 5% Light (21% Power)
Full-1/2-Off	Down to 10% Light (19% Power)
Full-2/3-1/3-Off	Down to 20% Light (36% Power)
Full – 1/2	Down to 30% Light (30% Power)
Full – 2/3	-
Full – 2/3 – 1/3	-

2.3. Simulation

E-Quest is considered as an energy modeling software to simulate and compare lighting, cooling, and total electrical energy consumption of the building through using various types of daylight control systems. Within this energy modeling software which meets ASRAE 90.1 standards, the simulation engine is derived from the most recent version of DOE-2 which has been extended and expanded in several ways such as interactive operation and dynamic/intelligent defaults. This simulation tool also encompasses a dynamic daylighting model to evaluate the impacts of natural light on thermal and lighting demand of the building [30]. The software offers an option in which a specific type of daylight controller could be selected. Then, the selected controller is placed in the building based on building zones definition as well as the defined distance of that from the windows.

In order to achieve more accurate results, we divided each floor of the open office to 8 zones measuring 9m x 9m each. Two daylight sensors were considered for each zone placing 3m and 6m far from windows measuring daylight illuminance level at a height of 0.8m. E-Quest placed each daylight sensor based on the defined criteria in each defined zone (Figure 5).

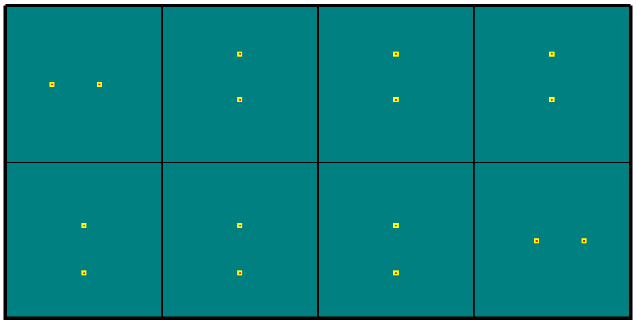

Figure 5. 8 zones and locations of daylight sensors in each zone (typical for all floors)

Another important factor on performance of the daylight control systems is the indoor illuminnace level on working plane. According to Illumination Engineering Society (IES) [31], the best range of illuminance level for open offices is 300-500 lux at working plane. In this study, an illuminace level of 400lux at working plane (0.8m) was defined as an average for the virtual office environment. In presented research, location, WWR, and daylighting controller types are variables and other characteristics of the office remained as the software's default options. Considering 11 types of daylight control strategies (no daylight controller as the base case, 6 Stepped, and 4 Dimming) as well as 3 cities and 4 WWRs, 132 simulations have been run throughout this study.

Lighting Power Density (LPD) is also a significant measure which impacts lighting and total electrical energy consumption of the buildings is. Lighting Power density is defined as lighting energy (watts) per unit of space. Allowable LPD varies based on the type and function of each space. Based on ASHRAE 90.1, maximum allowable LPD for open offices is 11.8 W/m^2 which was considered for this simulation. Moreover, there are always other electrical loads resulting from electrical equipment and devices that are not responsible for space heating, cooling, lighting, and water heating. These are called miscellaneous loads. In this simulation, a miscellaneous load of 8 W/m^2

was determined based on ASHRAE 90.1 for the virtual open office.

3. Results and Discussion

Based on the results obtained from simulations in this study, both daylight controllers types and WWR are influential factors on lighting, cooling, and total electrical consumption of an office building located in hot and arid climate. In general, regardless of WWR, all types of daylight controllers improve lighting and cooling electrical energy consumption of the buildings significantly. Figure 6 illustrates the amount annual lighting electrical energy that is consumed in the virtual office with WWR of 40 percent for various types of control systems.

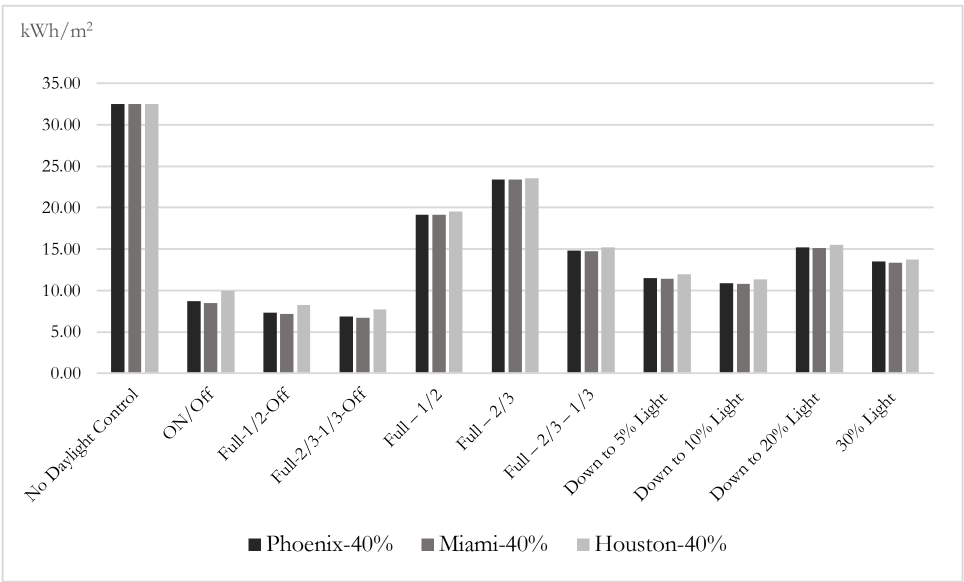

Figure 6. Annual lighting energy consumption for the virtual office building with WWR of 40%

As indicated, all daylight controllers reduce lighting energy consumption of the virtual office buildings. These finding are aligned with those reported by previous studies [6, 11, 13, 31]. However, the amount of energy saving varies for different control systems. Based on Figure 6, more lighting energy savings obtain through installing On/Off, Full-1/2/Off, and Full-2/3-1/3-Off controllers and all of them are in Stepped category. It means that Stepped daylight controllers with an “Off” step provide more energy savings compared to those of Dimming in hot climates. Previous studies reported different results regarding the energy saving potential of Dimming and Stepped daylight controllers. Ferreira [12] found out that, in tropical climates, using Dimming daylight control systems associated with more lighting energy savings compared to those of Stepped, while Li et al. [13] stated that the efficiency of daylight controllers in terms of lighting energy savings depends on the target illuminace level, weather conditions, and number and location of photosensors. As in present study, all selected cities had a sufficient rate of annual average illumination and clear sky conditions, the simulation indicated more lighting energy savings by using Stepped daylight controllers. The reason is that under sufficient daylighting illuminace level in the office, these types of controllers turn off lighting fixtures totally (On/Off) or partially (Full-1/2/Off, and Full-2/3-1/3-Off) while Dimming controllers dim the power and lumen output of the fixtures to achieve the predetermined illuminance level and never turn them off completely. Therefore, compare to Dimming daylight controllers, those Stepped which include "Off" step can save more lighting energy. However, the other three Stepped controllers, Full-1/2, Full-2/3, and Full-2/3-1/3 that do not have "Off" state are the least efficient ones among all controllers. Based on the simulation results, among Stepped controllers, Full-2/3-1/3-Off controllers with 4 steps could save up to 79 percent lighting energy consumption annually. Consequently, we might conclude that number of steps in control system and the way these steps are scheduled are another variables which impact lighting energy consumption of the buildings. Considering more steps means lighting fixtures could be turned off or on gradually based on available daylight illuminance level and building's lighting system is able to adjust itself with daylighting condition more accurately and thus more energy savings may be achieved. Ihm et al. [26] also found out a positive correlation between number of steps and the amount lighting energy saving for various climate conditions.

Although results of this study demonstrate that Stepped control systems are more efficient, under inconsistent weather conductions and daylight availability these systems turn on and off lighting fixtures frequently which might disturb occupants and reduce lamp life. Therefore, they could be a proper daylight control solution where the weather condition is consistent and a sufficient amount of daily daylight is available. For other conditions, using Dimming daylight control systems is more desirable. Dimming control systems could improve lighting energy consumption of the building by 55-65 percent. This result is almost consistent with that of reported in pervious field studies [13]. However, it should be considered that the amount of energy saving attains form Dimming systems depends on percentage of power reduction and not that of lighting output. For instance, as indicated in Table 7, Dimming controller of down to 5% light reduces power up to 21% while down to 10% one can dim power to 19%. Consequently, Dimming system of 10% light is more efficient and saves the most energy among all Dimming systems. The more power reduction associated by Dimming daylight controllers means the system is more efficient and save more lighting energy.

3.1. Impacts of Daylight Controllers on Cooling and Total Energy

Compared to natural light, electrical lightings generate more heat in order to achieve the same amount of illuminence level. As a result, regardless of types, all daylight control systems decrease cooling energy consumption of the building. Figure 7 shows the amount cooling energy consumed by the virtual office with WWR of 40% using various types of daylight controllers located in Phoenix, Miami, and Houston. Results demonstrate that installing daylight control systems in office buildings saves 8-16% of annual cooling energy in hot climates. Moreover, various types of controllers have almost the same impacts on cooling energy consumptions and there is a negligible difference among their efficiency in terms of cooling energy savings. These findings are consistent with those of the previous studies conducted by Ahn et al. [33] and Tzempelkikos and Athienitis [34-36] in different climates. Ahn et l. [33] reported that applying daylighting controllers is more beneficial in hot and humid climates compared to other climates and more cooling energy could be saved. This is resulting from significant amount of lighting energy savings due to the high rate of daylight availability. Enhancement of cooling energy is particularly essential in hot and arid climates in which cooling demand is an immense part of electrical load. However, rather than daylighting control strategy, cooling energy is more influenced by location and WWR which will be discussed in the following section.

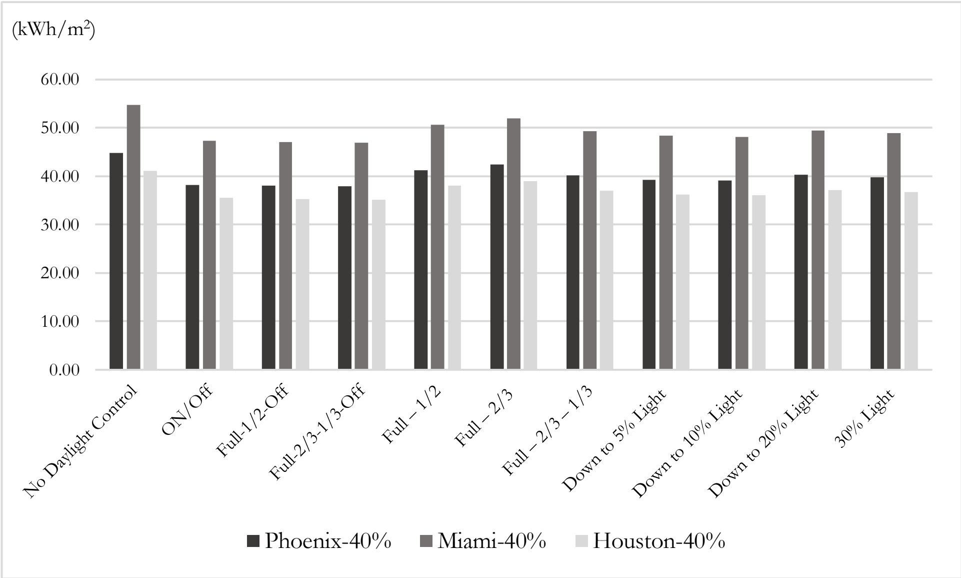

Figure 7. Annual cooling energy consumption

In addition, results from simulation demonstrated that using daylight controllers in the virtual office building in selected cities reduces annual electrical energy consumption (Figure 8) and provides up to 30% of total electrical energy savings. The amount of saving varies depend on control types. Among examined daylight controllers, On/Off, Full-1/2-Off and Full-2/3-1/3-Off daylight sensors provide the most annual electrical energy savings (27-30%). This happens as a result of larger amount of lighting energy saving with Stepped controllers. These findings confirm the results from pervious field and simulation based studies [8, 10, 11, 12, 37-40]. However, none of these studies compared the performance of various types of daylight control systems. It has been reported that compared to other climates, more electrical energy saving is resulted by employing daylight controllers in hot and arid climates which have a high cooling demands [33]. This happens due to a significant reduction in both lighting and cooling energy consumption.

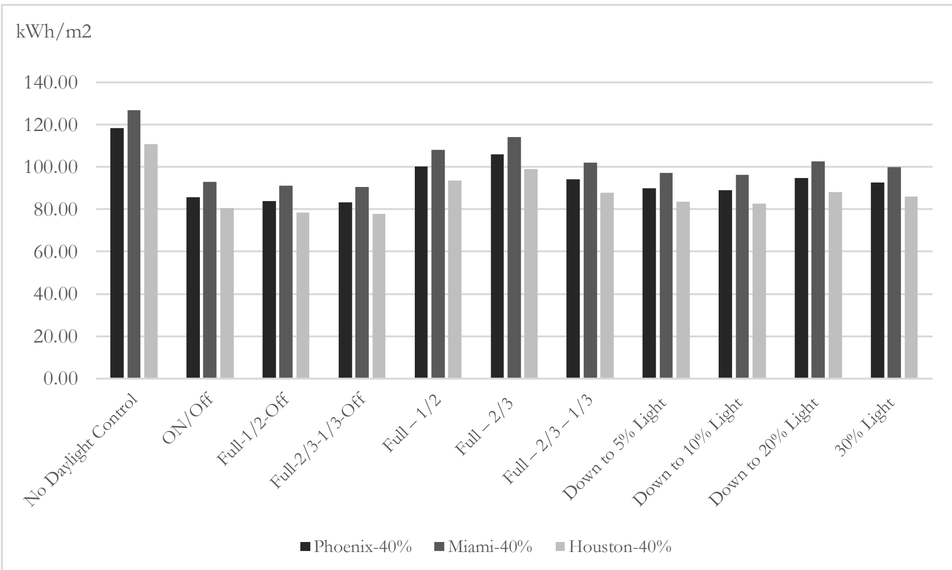

Figure 8. Annual electrical energy consumption

3.2. Impacts of WWR on Lighting, Cooling, and total energy consumption of the building

Window to Wall Ratio (WWR) is one of the most important variables that affects the amount daylight availability in indoor environment and as a result it is influential on efficacy of daylight sensors and control systems. Results of this study demonstrate that higher WWR leads to more lighting energy savings when a daylight control system is installed in the building. Pervious literature has also reported the same findings [34, 41]. Figure 9 shows the percentage of lighting energy savings associated by various types of daylight controllers for 4 different WWRs (20%, 40%, 60%, and 90%) in 3 selected cities. As shown in the bar charts, with WWR of 90%, On/Off, Full-1/2-Off, and Full-2/3-1/3-Off daylight controllers are able to save up to 83% of the annual lighting energy. Although increasing WWR enhances lighting energy savings due to more daylight availability, it impacts cooling energy consumption negatively for the same reason. Sun light in indoor environment heats up the space and more energy will be required to cool the space. In addition, considering more and larger fenestrations for the building reduces building's insulations. In hot and arid climates, it causes more heat transmitted into the indoor environment and increases temperature of the space. Therefore, generally more WWR brings about more cooling loads in all three selected cities (Figures 10). In this study, we achieved more cooling energy savings for WWR of 20% for most control strategies. However, for On/Off controllers in all selected cites as well as Full-1/2-Off and Full-2/3-1/3-Off daylight controllers in Phoenix, WWR of 40% seems more efficient in terms of cooling loads. As indicated, WWR influences lighting and cooling energy inversely. Consequently, in order to find the optimum WWR, we need to consider total electrical energy consumption under different WWRs. Based on data illustrated in Figure 11, the amount of saving resulting from using daylight controllers depends on control types and WWR. Results of the study show that in all cities, On/Off, Full-1/2-Off and Full-2/3-1/3-Off daylight sensors with WWR of 40% provide the most annual electrical energy savings (27-30%). For all types of daylight controllers in all cities, WWR of 90% provides the least amount of savings due to significant increase in cooling loads. In fact, a number of other studies revealed that WWR of 30-40% is the most optimized ratio in terms of buildings energy saving. An increase in WWR does not offer any significant additional energy savings and creates risks for glare and overheating. Large WWR is even more devastating in hot and arid climates and might cause abusive use of shading devices which leads to reduced daylight benefit [42].

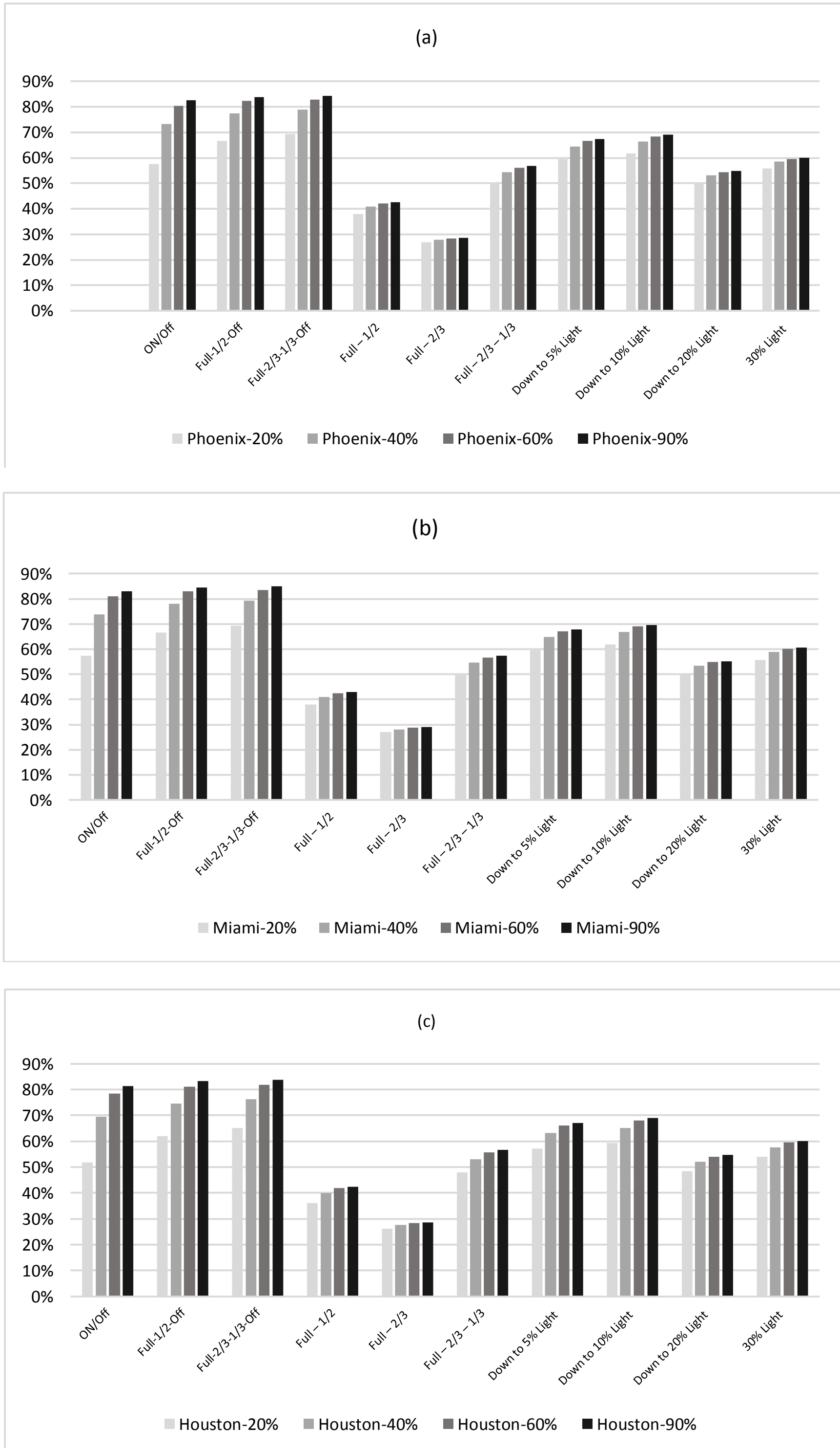

Figure 9. Lighting energy savings for various WWRs. (a) Phoenix, (b) Miami, (c) Houston

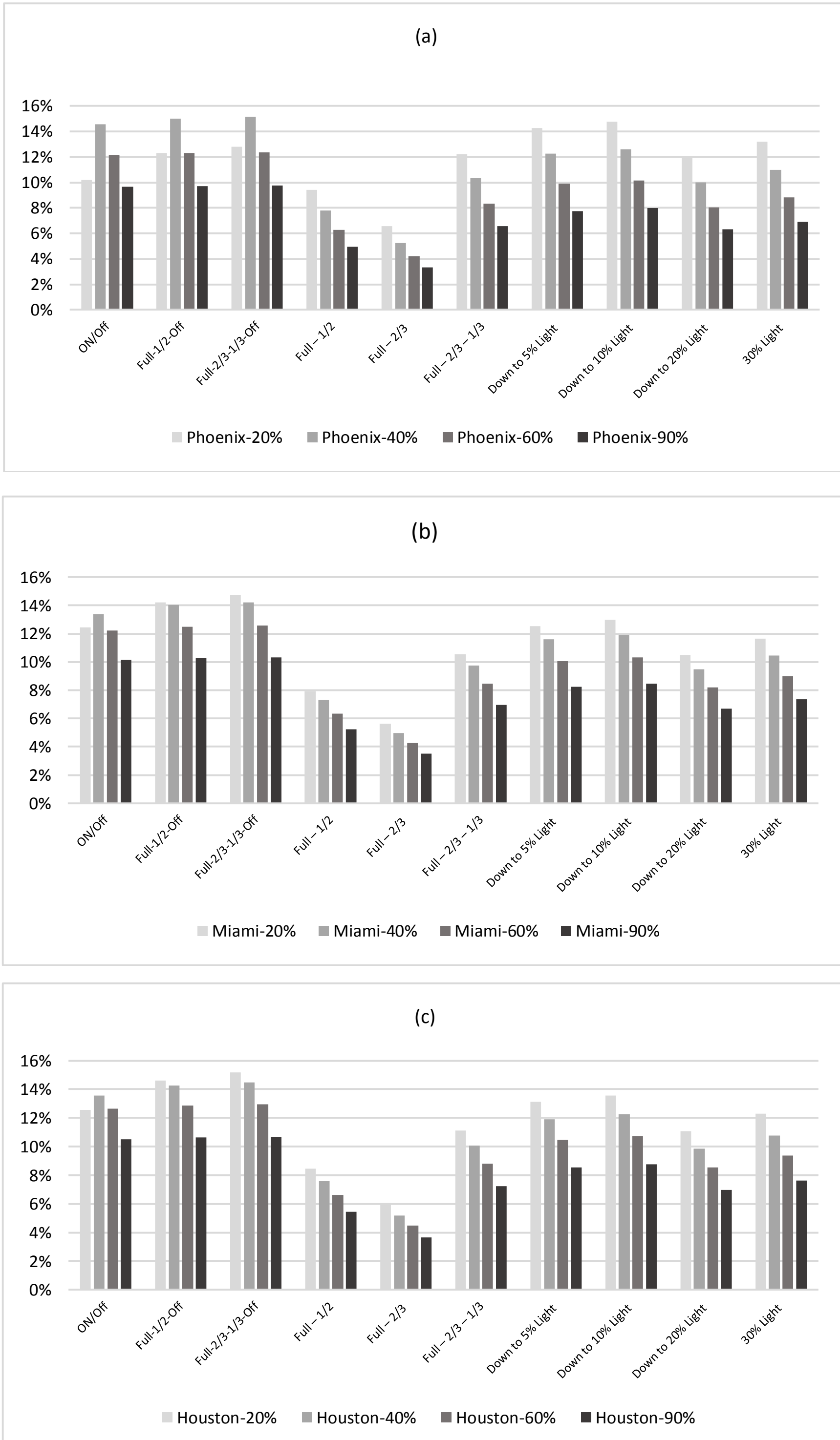

Figure 10. Cooling energy savings for various WWRs. (a) Phoenix, (b) Miami, (c) Houston

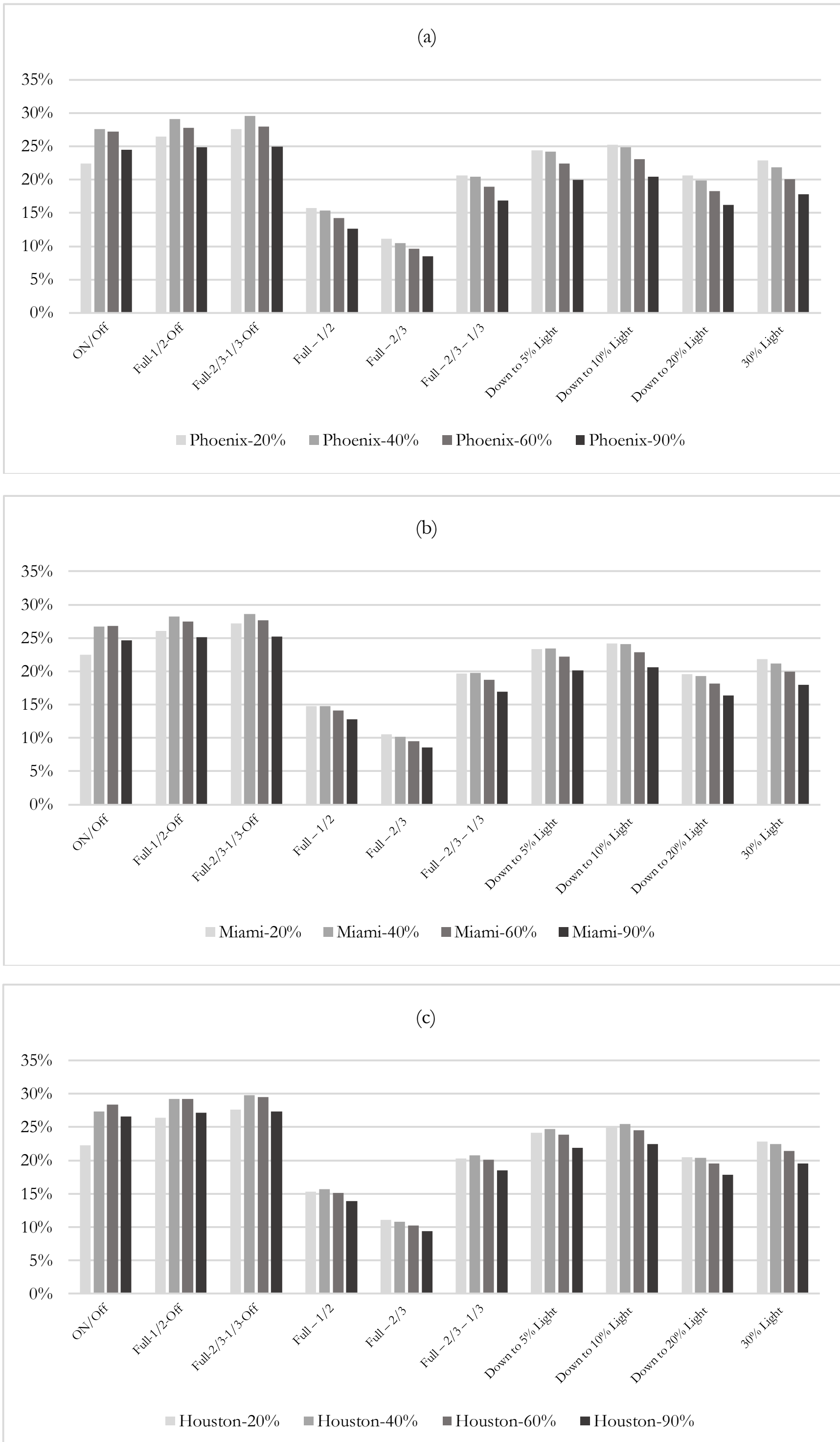

Figure 11. Total Electrical energy savings for various WWRs. (a) Phoenix, (b) Miami, (c) Houston

4. Conclusion

In this study, impacts of daylight control systems on lighting, cooling, and total electrical energy consumption of office buildings located in hot and arid climates were assessed through simulation. Results of the study demonstrate that installing daylight controllers is able to save up to 85% of lighting energy, 15% of cooling energy and 30% of total electrical energy consumption of an office in hot climates. The amount of saving varies depend on controllers' types and WWR and the impact of controllers' type is more significant. Among 10 types of control systems evaluated in this study, On/Off, Full-1/2-Off and Full-2/3-1/3-Off daylight sensors which are all Stepped systems provided the most energy savings. However, since Stepped controllers could be disturbing under inconsistent weather conditions, using Dimming control systems is more desirable. We also concluded that the number of steps could impact the efficiency of controllers. Defining more steps means we may achieve more energy savings from Stepped control systems.

In addition, we found out that WWR impacts lighting and cooling energy inversely. More WWR provides more lighting energy savings due to more daylight exposure and less cooling energy savings for the same reason. For most types of daylight controllers that have been evaluated in this paper, it seems that in hot and arid climates WWR of 40 percent provides the most electrical energy savings.

However, one limitation with this study was that we only examined the impacts of daylight controllers with a closed loop algorithm due to software limitations, while for some conditions using open loop system is more appropriate. Further studies need to be conducted in order to examine and compare the efficiency of various daylight controller with these open and closed loop algorithms. In addition, the virtual office we simulated in this study was a standalone building with no surrounding obstacles. In the real situation, there are usually physical obstacles such as other buildings and trees which might significantly impact the amount of daylight availability inside the office building. Future studies should be considered to evaluate how surrounding obstacles impacts the amount of lighting, cooling, and total electrical energy consumption of the building using various types of daylight controllers. Moreover, interior obstacles resulting from interior design and furniture placement are another influential factor in determining daylight availability inside the building. In this study, we simulated an open office with no furniture or interior walls. In order to have more precise results, we need to repeat this study for actual office buildings with defined interior spaces and furniture.

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